

**TRANSMITTAL LETTER TO THE UNITED STATES  
DESIGNATED/ELECTED OFFICE (DO/EO/US)  
CONCERNING A FILING UNDER 35 U.S.C. 371**

U.S. APPLICATION NO. (If known, see 37 CFR 1.5)

**09/8561 08**INTERNATIONAL APPLICATION NO.  
**PCT/EP99/08206**INTERNATIONAL FILING DATE  
**29 October 1999**  
(29.10.99)PRIORITY DATE CLAIMED:  
**17 November 1998**  
(17.11.98)TITLE OF INVENTION  
**ELECTRO-OPTICAL LIGHT MODULATOR**APPLICANT(S) FOR DO/EO/US  
**Wolfgang DULTZ; Leonid BERESNEV; Wolfgang HAASE; and Arkadii ONOKHOV**

Applicant(s) herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information

1. ☒ This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. ☒ This is an express request to begin national examination procedures (35 U.S.C. 371(f)) immediately rather than delay examination until the expiration of the applicable time limit set in 35 U.S.C. 371(b) and PCT Articles 22 and 39(1).
4. ☐ A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date.
5. ☒ A copy of the International Application as filed (35 U.S.C. 371(c)(2))
  - a. ☐ is transmitted herewith (required only if not transmitted by the International Bureau).
  - b. ☒ has been transmitted by the International Bureau.
  - c. ☐ is not required, as the application was filed in the United States Receiving Office (RO/US)
6. ☒ A translation of the International Application into English (35 U.S.C. 371(c)(2)).
7. ☒ Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371(c)(3))
  - a. ☐ are transmitted herewith (required only if not transmitted by the International Bureau).
  - b. ☐ have been transmitted by the International Bureau.
  - c. ☐ have not been made; however, the time limit for making such amendments has NOT expired.
  - d. ☒ have not been made and will not be made.
8. ☐ A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).
9. ☒ An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)) **UNSIGNED**.
10. ☐ A translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).

**Items 11. to 16. below concern other document(s) or information included:**

11. ☒ An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
12. ☐ An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
13. ☒ A **FIRST** preliminary amendment.  
☐ A **SECOND** or **SUBSEQUENT** preliminary amendment.
14. ☒ A substitute specification and a marked up version of the substitute specification.
15. ☐ A change of power of attorney and/or address letter.
16. ☒ Other items or information: International Search Report and Form PCT/RO/101.

Express Mail No.: EL245834230US

- 17.
- ☒
- The following fees are submitted:

**Basic National Fee (37 CFR 1.492(a)(1)-(5)):**

Search Report has been prepared by the EPO or JPO ..... \$860.00

International preliminary examination fee paid to USPTO (37 CFR 1.482) ..... \$690.00

No international preliminary examination fee paid to USPTO (37 CFR 1.482) but  
international search fee paid to USPTO (37 CFR 1.445(a)(2)) ..... \$710.00Neither international preliminary examination fee (37 CFR 1.482) nor international  
search fee (37 CFR 1.445(a)(2)) paid to USPTO ..... \$1,000.00International preliminary examination fee paid to USPTO (37 CFR 1.482) and all  
claims satisfied provisions of PCT Article 33(2)-(4) ..... \$100.00**ENTER APPROPRIATE BASIC FEE AMOUNT =**

\$ 860

Surcharge of \$130.00 for furnishing the oath or declaration later than ☐ 20 ☐ 30 months  
from the earliest claimed priority date (37 CFR 1.492(e)).

\$

Claims	Number Filed	Number Extra	Rate		
Total Claims	15 - 20 =	0	X \$18.00	\$0	
Independent Claims	2 - 3 =	0	X \$80.00	\$0	
Multiple dependent claim(s) (if applicable)			+ \$270.00	\$	

**TOTAL OF ABOVE CALCULATIONS =**

\$860

Reduction by 1/2 for filing by small entity, if applicable. Verified Small Entity statement must  
also be filed. (Note 37 CFR 1.9, 1.27, 1.28).

\$

**SUBTOTAL =**

\$860

Processing fee of \$130.00 for furnishing the English translation later the ☐ 20 ☐ 30  
months from the earliest claimed priority date (37 CFR 1.492(f)).

\$

**TOTAL NATIONAL FEE =**

\$860

Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be  
accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). \$40.00 per property

\$

**TOTAL FEES ENCLOSED =**

\$860

Amount to be  
refunded  
charged\$  
\$

- a. ☐ A check in the amount of \$\_\_\_\_\_ to cover the above fees is enclosed.
- b. ☒ Please charge my Deposit Account No. 11-0600 in the amount of \$860.00 to cover the above fees. A duplicate copy of this sheet is enclosed.
- c. ☒ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. 11-0600. A duplicate copy of this sheet is enclosed.

**NOTE:** Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

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5/17/2001

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09/8561 08

J608 Rec'd PCT/PTO 17 MAY 2007

[2345/155]

**IN THE UNITED STATES PATENT AND TRADEMARK OFFICE**

Applicant(s) : Wolfgang DULTZ et al.  
Serial No. : To Be Assigned  
Filed : Herewith  
For : ELECTRO-OPTICAL LIGHT MODULATOR  
Art Unit : To Be Assigned  
Examiner : To Be Assigned

Assistant Commissioner  
for Patents  
Washington, D.C. 20231

**PRELIMINARY AMENDMENT AND  
37 C.F.R. § 1.125 SUBSTITUTE SPECIFICATION STATEMENT**

SIR:

Please amend the above-identified application before examination, as set forth below.

**IN THE TITLE:**

Please replace the title with the following:

--ELECTRO-OPTICAL LIGHT MODULATOR--.

**IN THE SPECIFICATION AND ABSTRACT:**

In accordance with 37 C.F.R. § 1.121(b)(3), a Substitute Specification (including the Abstract, but without claims) accompanies this response. It is respectfully requested that the Substitute Specification (including Abstract) be entered to replace the Specification of record.

**IN THE CLAIMS:**

Without prejudice, please cancel original claims 1 to 15 in the underlying PCT application and please add new claims 16 to 30 as follows:

EL24583423045

--16. (New) An electrically drivable light modulator comprising:

at least two liquid crystal layers for enclosing between at least two transparent plates having a surface anisotropy for orienting molecules of the at least two liquid crystal layers and having electrodes for generating an electric field in the at least two liquid crystal layers; wherein:

the at least two liquid crystal layers include helical, smectic ferroelectric liquid crystals, whose fast optical axes and slow optical axes, respectively, are disposed in parallel with a respective one of the at least two liquid crystal layers, and whose average optical anisotropy is influenceable by an action of the electric field;

the at least two liquid crystal layers are situated one behind another for being in a path of rays of a light beam to be modulated; and

directions of the fast optical axes and slow optical axes, respectively, of the at least two liquid crystal layers are rotated relative to one another so that a polarization upstream of the light beam is the same as a polarization downstream of the light beam.

17. (New) The electrically drivable light modulator of claim 16, wherein the at least two liquid crystal layers include a first layer and a second layer and are situated one behind another so that:

a first slow optical axis of the first layer is normal to a second slow optical axis of the second layer;

a first fast optical axis of the first layer is normal to a second fast optical axis of the second layer; and

an orientation of the first slow optical axis and the first fast optical axis of the first layer and of the second slow optical axis and the second fast optical axis of the second layer in relation to one another is retained at all times when a control voltage is applied and varied.

18. (New) The electrically drivable light modulator of claim 16, wherein the at least two liquid crystal layers are enclosed between the at least two transparent plates, and a control voltage is applied to the electrodes for generating the electric field.

19. (New) The electrically drivable light modulator of claim 16, wherein the at least two transparent plates include a plurality of transparent plates, and each of the at least two liquid

crystal layers is enclosed between two of the plurality of transparent plates, a control voltage being applicable to the electrodes for generating a respective electric field in each case.

20. (New) The electrically drivable light modulator of claim 16, wherein the at least two liquid crystal layers exhibit a same average refractive index, have a same thickness and are able to receive synchronously a same control voltage.

21. (New) The electrically drivable light modulator of claim 19, wherein a ratio of control voltages of the electrodes is adjustable for compensating for a change in the polarization of a light beam passing through the at least two liquid crystal layers.

22. (New) The electrically drivable light modulator of claim 16, wherein control voltages for each of the at least two liquid crystal layers is adjustable for compensating for a manufacturing tolerance.

23. (New) The electrically drivable light modulator of claim 16, wherein the at least two liquid crystal layers include a smectic liquid crystal mixture FLC-472/FLC-247.

24. (New) The electrically drivable light modulator of claim 16, wherein the at least two liquid crystal layers include 60 % by weight of phenyl pyrimidine and 40 % by weight of an achiral, smectic A matrix having a chiral doping on a basis of a disubstituted ether of bis-terphenyl dicarboxylic acid.

25. (New) The electrically drivable light modulator of claim 16, wherein the at least two liquid crystal layers include 60 % by weight of phenyl pyrimidine and 40 % by weight of an achiral, smectic C matrix having a chiral doping on a basis of a disubstituted ether of bis-terphenyl dicarboxylic acid.

26. (New) An adaptive optical device comprising:

a field of light modulators being configured in a raster-type array and being for situating in a path of rays, each of the light modulators being drivable for compensating for unsharpness occurring on a point-by-point basis of an image to be processed, and each of the light modulators including:

at least two liquid crystal layers for enclosing between at least two transparent plates having a surface anisotropy for orienting molecules of the at least two liquid crystal layers and having electrodes for generating an electric field in the at least two liquid crystal layers, wherein:

the at least two liquid crystal layers include helical, smectic ferroelectric liquid crystals, whose fast optical axes and slow optical axes, respectively, are disposed in parallel with a respective one of the at least two liquid crystal layers, and whose average optical anisotropy is influenceable by an action of the electric field;

the at least two liquid crystal layers are situated one behind another for being in a path of rays of a light beam to be modulated; and

directions of the fast optical axes and slow optical axes, respectively, of the at least two liquid crystal layers are rotated relative to one another so that a polarization upstream of the light beam is the same as a polarization downstream of the light beam.

27. (New) The adaptive optical device of claim 26, further comprising a common substrate for mounting the field of light modulators.

28. (New) The adaptive optical device of claim 26, wherein a digital camera is arranged upstream from an image sensor for picking up and feeding an image to an image-analysis device for determining a point-for-point unsharpness in the image, and the adaptive optical device is drivable by the image-analysis device for compensating for the point-for-point unsharpness.

29. (New) The adaptive optical device of claim 26, wherein an image observable by an optical observational device is feedable in parallel to an image-analysis device for determining a point-for-point unsharpness in the image, and the adaptive optical device is drivable by the image-analysis device for compensating for the point-for-point unsharpness.

30. (New) The adaptive optical device of claim 26, wherein an image observable by a camera is feedable to an image-analysis device for determining a point-for-point unsharpness

in the image, and the adaptive optical device is drivable by the image-analysis device for compensating for the point-for-point unsharpness.--

### REMARKS

This Preliminary Amendment cancels without prejudice original claims 1 to 15 in the underlying PCT Application No. PCT/EP99/08206, and adds without prejudice new claims 16 to 30. The new claims conform the claims to U.S. Patent and Trademark Office rules and do not add new matter to the application.

In accordance with 37 C.F.R. § 1.121(b)(3), the Substitute Specification (including the Abstract, but without the claims) contains no new matter. The amendments reflected in the Substitute Specification (including Abstract) are to conform the Specification and Abstract to U.S. Patent and Trademark Office rules or to correct informalities. As required by 37 C.F.R. § 1.121(b)(3)(iii) and § 1.125(b)(2), a Marked Up Version Of The Substitute Specification comparing the Specification of record and the Substitute Specification also accompanies this Preliminary Amendment. In the Marked Up Version, shading indicates added text and brackets indicated deleted text. Approval and entry of the Substitute Specification (including Abstract) is respectfully requested.

The underlying PCT Application No. PCT/EP99/08206 includes an International Search Report, dated February 16, 2000. The Search Report includes a list of documents that were uncovered in the underlying PCT Application. A copy of the Search Report accompanies this Preliminary Amendment.

Applicants assert that the subject matter of the present application is new, non-obvious, and useful. Prompt consideration and allowance of the application are respectfully requested.

Respectfully Submitted,  
KENYON & KENYON

Dated: 5/17/2001

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ELECTRO-OPTICAL LIGHT MODULATOR

The present invention is directed to an electrically drivable light modulator having liquid crystal layers, which are disposed one behind the other and are enclosed between transparent plates having a surface anisotropy that orients the molecules of the liquid crystals and having electrodes for generating an electric field in the liquid crystals.

Modulators of this kind are required for correcting the phases of light in a great variety of optical devices. Especially in the field of adaptive optics, efforts are intensifying to find ways to correct local unsharpness in the object image of a telescope or a camera, caused, for example, by atmospheric effects or thermal stresses in the equipment. Especially in connection with rapid digital image processing technology, ways are evolving to correct images that are so distorted. The image is corrected, even during observation, by an electronically drivable raster of optically active elements that is introduced into the optical path of rays of the object image. This leads one to imagine photographic and observational equipment, which delivers a sharp image even in the presence of strong disturbances.

Due to their electro-optical properties, liquid crystals can be used to control the phase of a light wave propagating through them, in that the refractive index of a layer of liquid crystals is influenced by an electric field. The principal electro-optical effects in liquid crystals alter both the birefringence as well as the orientation of the indicatrix of the refractive index of the liquid crystal. This is undesirable for most



applications, because not only does the anisotropic character of the liquid crystals produce a phase shift as it passes through the liquid crystal, but it changes the polarization as well. For that reason, only polarized  
5 light can be handled using liquid crystals of this kind. However, wavefront variations caused by phase lag ought to be possible, independently of polarization, for the above mentioned applications.

10 When nematic liquid crystals are used, the phase of a light beam can be changed without affecting the polarization of the light. Here as well, however, the light must be linearly polarized in parallel to the director of the oriented liquid crystal molecules. In  
15 addition, the reaction rate of such cells is too slow for applications in image-processing devices.

Ferroelectric liquid crystals (FLC) can be driven in a sufficiently short operation time. However, potential  
20 applications for ordinary ferroelectric liquid crystals are very limited due to the small phase changes that are attainable with. At cell thicknesses of  $10\mu\text{m}$ , phase shifts of merely about  $1/10$  of the wavelength of visible light are attained. However, one should aspire to phase  
25 shifts of one complete wavelength or more in order to perform all necessary phase corrections.

EP 0 309 774 describes a liquid crystal cell which employs the DHF effect (deformation of the helix  
30 structure in the electric field) that occurs in FLCs, for continuous phase control and for gray scale representation. The optical phase control is based on a pronounced change in the average refractive index of the liquid crystal resulting from an applied electric field.  
35 The change in the birefringence of the deformed helix structure can reach  $d(n) = 5\%$ ; the average refractive anisotropy  $\langle dn \rangle = 15\%$ . Due to the optical properties of

the helical structure of thereby employed chiral smectic liquid crystal in the electric field, the change in the birefringence is associated with marked changes in the orientation of the average optical indicatrix. This means that, after propagating through the liquid crystal, the light is in a polarization state which is heavily dependent upon the polarization state upon entry. This dependence precludes the use of the described cell for the required purposes.

In Love, Restaino, Carreras, Loos, Morrison, Baur and Kopp: "Polarization Insensitive 127-Segment Liquid Crystal Wavefront Corrector", Adaptive Optics, vol. 13, pp. 228-290, Optical Society of America, Washington D.C., 1996, an electro-optically functioning modulator for controlling the phase of unpolarized light is introduced that contains two liquid crystal layers of the nematic type, which are disposed one behind the other. In the cited work, the two nematic layers are situated such that the directors of the liquid crystals are disposed orthogonally to one another in the field-free state. However, as already mentioned above, the cell is much too slow for the purpose aspired to.

The object of the present invention is to provide an electrically drivable light modulator, whose switching time is on the order of 1060-460 seconds or less, given a maximum phase shift of over  $2\pi$ , and which can steplessly vary the phase of an arbitrarily polarized light beam, without altering its polarization state, and which is suited for fabricating highly resolving, adaptive optical devices, i.e., that is small, light, and low-loss.

This objective is achieved in accordance with the present invention in that at least two layers of helical, smectic, ferroelectric liquid crystals, whose fast and slow optical axes, respectively, are disposed in parallel

with the layer in question, and whose average optical anisotropy can be influenced by the action of the electric field, are situated one behind the other in the path of rays of a light beam to be modulated, and in that the directions of the fast and slow axes, respectively, of the individual layers are rotated relatively to each other in such a way that the polarization of the light beam is the same upstream and downstream from the modulator.

In this context, the "slow" axis corresponds to that direction in which the refractive index is the greatest. The "fast" axis is that direction in which the refractive index is the smallest. This means that the phase of a light beam that is polarized in the slow direction is delayed substantially, and the phase of a light beam that is polarized in the fast direction is delayed to a lesser extent. Thus, in the case of arbitrarily polarized light, the anisotropy of the refractive indices alters its polarization state as it passes through the liquid crystal layers. The rotation of the individual layers relatively to one another is exactly calculated to again effect a reversal of the mentioned change in the polarization state of the subsequent layers.

In the simplest case, the light modulator is so conceived that two liquid crystal layers are situated one behind the other such that the slow optical axis of the first layer is normal to the slow optical axis of the second layer, the fast optical axis of the first layer is normal to fast optical axis of the second layer, and the orientation of the slow and fast optical axes of the two layers in relation to one another is retained at all times during application and variation of the control voltage.

The fast and slow axes of the two layers intersecting at

right angles only just compensates for the variations in the birefringence and in the orientation of the indicatrix ellipsoids of the refractive indices.

5 To reduce the unit volume, provision can be made for the liquid crystal layers to be enclosed between two transparent plates, on whose electrodes a control voltage can be applied to generate an electric field.

10 On the other hand, to reduce the outlay for assembling the light modulator and to facilitate mass production, provision can alternatively be made for each of the liquid crystal layers to be enclosed between two transparent plates, on whose electrodes a control voltage  
15 can be applied in each case to generate an electric field.

To manufacture the light modulator in accordance with the present invention, the required number of individual  
20 cells, fabricated in this manner, is arranged one behind the other.

When using equivalent layer thicknesses and materials for the layers, it is provided that the liquid crystal layers  
25 exhibit the same average refractive indices, have the same thickness, and be able to synchronously receive the same control voltages.

On the other hand, when using different layer thicknesses  
30 or different materials for the individual layers, it is provided that the ratio of the control voltages to one another be adjustable to compensate for the changes in the polarization of a light beam passing through. In this manner, a crossing over of the main refractive directions  
35 can also be achieved in the case of asymmetrically constructed cells.

Considerable outlay is required to manufacture the liquid crystal cells; large quantities do not meet the requirements for accuracy and must, therefore, be sorted out and reintroduced to the production process. To  
5 simplify production and reduce associated costs, it is provided that the control voltages be adjustable for the individual liquid crystal layers to compensate for manufacturing tolerances.

10 The light modulator in accordance with the present invention works particularly well in the range of visible light with a smectic liquid crystal mixture FLC-472/FLC-247 of 60 % by weight of phenyl pyrimidine and 40 % by weight of an achiral, smectic A or C matrix  
15 having a chiral doping on the basis of disubstituted ether of bis-terphenyl dicarboxylic acid. This doping induces a spontaneous polarization of about 160 nC/cm<sup>2</sup> in the matrix having a helical structure of the winding period of about 0.3  $\mu$ m in the chiral smectic phase. An  
20 operating voltage of 0V to 4V already produces a smectic deflection angle of 0° to  $\pm 22.5^\circ$  at a response time 122 of 150  $\mu$ s. Thus, the modulation depth between two crossed layers amounts up to 100%. In response to the operating voltage mentioned above, the average refractive index  
25 already changes by amounts of up to 5%. To obtain a phase difference on the order of the wavelength of the light to be controlled, a summed layer thickness of 10  $\mu$ m suffices. This layer thickness is the sum of the thicknesses of the individual layers.

30 When cameras or telescopes are used to observe objects within or right through the earth's atmosphere, local unsharpness occurs in the object image which is attributable to atmospheric disturbances. To correct this  
35 local unsharpness, an adaptive optical device is proposed which contains a field of light modulators, in a raster-type array, of the type described by the present

invention. The field is situated in the path of rays of the device, each individual light modulator being able to be driven to compensate for unsharpness occurring on a point-by-point basis, of an image to be processed.

5

In this context, to reduce the outlay for assembly, the light modulators can be mounted on a common substrate.

10

The device is positioned in the ray path of the observational equipment in question, such as a camera or telescope. The object image picked up by the observational equipment is fed to an image-analysis device, which determines the unsharpness in the image and, to compensate for the same, drives the modulator field accordingly.

15

One exemplary embodiment of the light modulator of the present invention is illustrated in the drawing on the basis of a plurality of figures, which show:

20

Figure 1 the configuration of the liquid crystal cells for the modulator; and

25

Figure 2 a schematic diagram of the refractive index indicatrices for the various operating states.

(Equivalent parts in the figures are provided with the same reference numerals.)

30

Figure 1 depicts the two liquid crystal layers 6 and 9 disposed one behind the other in the ray trajectory of a light beam 10 to be modulated. The polarization direction of incident light beam 10 and of emergent light beam 11 is marked in each case by a double arrow. In the example, the polarization direction of incident light beam 10 is tilted by angle  $\theta$  from the perpendicular.

35

First liquid crystal layer 6 is situated between two transparent electrodes 1 and 2, which are mounted on two transparent plates 1' and 2'. Smectic layers 12 form displacement domains, along which the molecules of the liquid crystal arrange themselves. The molecules of the liquid crystal are twisted by an angle from layer to layer, so that the result is a helical structure whose axis 7 runs in the direction of normals  $z'$  to smectic layers 12. Second liquid crystal layer 8 is disposed between transparent electrodes 3 and 4, which are mounted, in turn, on transparent plates 3' and 4'. The direction of normal  $z''$  of smectic layers 13 of 122 second liquid crystal layer 8 and the axis of helix 9 are twisted by 90° from direction of normal  $z'$  and helical axis 7 of first layer 6.

Two liquid crystal layers 6 and 8, crossed in this manner, change the polarization state of a transmitted light beam 10. The pure phase modulation of the two liquid crystal layers is induced by the field-dependent, average refractive index. The birefringence and orientation effects of the indicatrix in the electric fields produced by the application of a voltage to connection terminals 5 are compensated in all field strengths.

Figure 2 shows the effects of an electric field  $E$  of variable strength 0,  $E'$ ,  $E''$  on refractive indices  $n_{20s20}$  and  $n_{20p20}$  of liquid crystal layers 6 and 8. The  $x$ - and  $z$ -axis of the illustrated coordinate system are disposed in parallel to the plane of the liquid crystal layers. In addition, the  $z$ -axis is situated in parallel to the direction of normal  $z'$  of first liquid crystal 6. The  $y$ -axis points in the direction of propagation of incident light beam 10. In Illustration a), no voltage is applied. The slow axis having refractive index  $n_{20p20}$  of the first liquid crystal layer points in the direction of the

z-axis, while the slow axis having refractive index  $n_{20p20}$  of the second liquid crystal layer is oriented orthogonally to the z-axis. The polarization state of the incident light is retained upon passing through both layers 6 and 8.

In Illustration b), a small voltage is applied which is less than that voltage at which the helical structure disappears. The slow optical axes having refractive indices  $n_{20p20}'$ , as well as the fast axes having refractive indices  $n_{20s20}'$  of both layers 6 and 8 reorient themselves and are rotated by angle  $\phi$ . The right angles between the axes are retained. The 122 refractive index  $n_{20p20}'$  increases in the slow axes with rising field strength  $E'$ , while refractive index  $n_{20s20}'$  decreases in the slow axes. The optical path of the transmitted light is changed by field strength  $E'$  and, consequently, is shifted in phase. The greatest change in the optical path occurs at a voltage that is just below that voltage at which the helical structure of the liquid crystal disappears. This state is shown in Illustration c). In the liquid crystals, which at this point are no longer wound, the index ellipsoid of the refractive indices is characterized by molecular refractive indices  $n_{20p20}''$  and  $n_{20s20}''$ . The slow axes having refractive indices  $n_{20p20}''$  are tilted in the two layers 6 and 8 by the molecular tilt angle  $T$ , which corresponds to the angle between smectic layers 12 and 13 and helical axes 7 and 9. In this case, as well, the axes remain crossed at a right angle. The phase displacement is, therefore, independent of the polarization of the light over the entire operating range. As a result, it is possible to control unpolarized light as well.



What is claimed is:

1. An electrically drivable light modulator having liquid crystal layers, which are disposed one behind the other and are enclosed between transparent plates having a surface anisotropy that orients the molecules of the liquid crystals and having electrodes for generating an electric field in the liquid crystals, wherein at least two layers (6, 8) of helical, smectic, ferroelectric liquid crystals, whose fast and slow optical axes, respectively, are disposed in parallel with the layer (6, 8) in question, and whose average optical anisotropy can be influenced by the action of the electric field (E), are situated one behind the other in the path of rays of a light beam (10) to be modulated, and in that the directions of the fast and slow axes, respectively, of the individual layers (6, 8) are rotated relatively to each other in such a way that the polarization of the light beam is the same upstream (10) and downstream (11) from the modulator.

2. The light modulator as recited in Claim 1, wherein the two liquid crystal layers (6, 8) are situated one behind the other such that the slow optical axis of the first layer (6) is normal to the slow optical axis of the second layer (8), the fast optical axis of the first layer (6) is normal to the fast optical axis of the second layer (8), and the orientation of the slow and fast optical axes of the two layers (6, 8) in relation to one another is retained at all times during application and variation of the control voltage.

3. The light modulator as recited in one of the preceding claims, wherein the liquid crystal layers are enclosed between two transparent plates, on whose electrodes a control voltage can be applied to generate an electric field.

4. The light modulator as recited in either Claim 1 or 2, wherein the liquid crystal layers (6, 8) are enclosed in each case between two transparent plates (1' and 2', 3' and 4'), on each of whose electrodes (1 and 2, 3 and 4) a control voltage can be applied to generate an electric field (E) in each case.

5. The light modulator as recited in one of the preceding claims, wherein the liquid crystal layers (6, 8) exhibit the same average refractive indices, have the same thickness, and are able to synchronously receive the same control voltages.

6. The light modulator as recited in Claim 4, wherein the ratio of the control voltages to one another is adjustable to compensate for the changes in the polarization of a light beam passing through.

7. The light modulator as recited in one of the preceding claims, wherein the control voltages for the individual liquid crystal layers are adjustable in order to compensate for manufacturing tolerances.

8. The light modulator as recited in one of the preceding claims, wherein the liquid crystal layers are composed of a smectic liquid crystal mixture FLC-472/FLC-247.

9. The light modulator as recited in one of the preceding claims,  
wherein the liquid crystal mixture is composed of 60 % by weight of phenyl pyrimidine and 40 % by weight of an achiral, smectic A matrix having a chiral doping on the basis of disubstituted ether of bis-terphenyl dicarboxylic acid.

10. The light modulator as recited in one of Claims 1 through 8,  
wherein the liquid crystal mixture is composed of 60 % by weight of phenyl pyrimidine and 40 % by weight of an achiral, smectic C matrix having a chiral doping on the basis of disubstituted ether of bis-terphenyl dicarboxylic acid.

11. An adaptive optical device,  
characterized by a field of light modulators, configured in a raster-type array, according to one of the preceding claims, the field being situated in the path of rays of the device, and each individual light modulator being able to be driven to compensate for unsharpness occurring on a point-by-point basis, of an image to be processed.

12. The adaptive optical device as recited in Claim 11,  
wherein the light modulators are mounted on a common substrate.

13. The adaptive optical device as recited in one of Claims 11 or 12,  
characterized by the arrangement of a digital camera upstream from the image sensor, the image picked up by the camera being able to be fed to an image-analysis device to determine point-for-point unsharpness in the image, and the adaptive optical device being able to be driven by the image-analysis device to compensate for the unsharpness.

14. The adaptive optical device, as recited in one of Claims 11 or 12, characterized by the arrangement in an optical observational device, the image to be observed being able to be fed in parallel to an image-analysis device to determine point-for-point unsharpness in the image, and the adaptive optical device being able to be driven by the image-analysis device to compensate for the unsharpness.

15. The adaptive optical device, as recited in one of Claims 11 or 12, characterized by the arrangement in a camera, the image to be observed being able to be fed to an image-analysis device to determine point-for-point unsharpness in the image, and the adaptive optical device being able to be driven by the image-analysis device to compensate for the unsharpness.

## Abstract

In the case of an electrically drivable light modulator having liquid crystal layers, which are disposed one behind the other and are enclosed between transparent plates having a surface anisotropy that orients the molecules of the liquid crystals and having electrodes for generating an electric field in the liquid crystals, at least two layers of helical, smectic, ferroelectric liquid crystals are situated one behind the other in the path of rays of a light beam to be modulated. The directions of the fast and slow axes, respectively, of the individual layers are rotated relatively to each other in such a way that the polarization of the light beam is the same upstream and downstream from the modulator. An adaptive, optical device is indicated, which has a field of light modulators configured in a raster-type array. The modulators are situated in the path of rays of the device, each individual light modulator being able to be driven to compensate for unsharpness occurring on a point-by-point basis, of an image to be processed.

ELECTRO-OPTICAL LIGHT MODULATOR

FIELD OF THE INVENTION

The present invention relates to an electrically drivable light modulator having liquid crystal layers, which are disposed one behind the other and are enclosed between  
5 transparent plates having a surface anisotropy that orients the molecules of the liquid crystals and having electrodes for generating an electric field in the liquid crystals.

BACKGROUND INFORMATION

Electrically drivable light modulators may be required for correcting the phases of light in a great variety of optical devices. Especially in the field of adaptive optics, efforts are intensifying to find ways to correct  
10 local unsharpness in the object image of a telescope or a camera, caused, for example, by atmospheric effects or thermal stresses in the equipment. Especially in connection with rapid digital image processing technology, ways are evolving to correct images that are  
15 so distorted. The image is corrected, even during observation, by an electronically drivable raster of optically active elements that is introduced into the optical path of rays of the object image. This leads one to imagine photographic and observational equipment,  
20 which delivers a sharp image even in the presence of strong disturbances.

Due to their electro-optical properties, liquid crystals can be used to control the phase of a light wave  
30 propagating through them, in that the refractive index of a layer of liquid crystals is influenced by an electric field. The principal electro-optical effects in liquid

SUBSTITUTE SPECIFICATION

crystals alter both the birefringence as well as the orientation of the indicatrix of the refractive index of the liquid crystal. This is undesirable for most applications, because not only does the anisotropic character of the liquid crystals produce a phase shift as it passes through the liquid crystal, but it changes the polarization as well. For that reason, only polarized light can be handled using liquid crystals of this kind. However, wavefront variations caused by phase lag ought to be possible, independently of polarization, for the above mentioned applications.

When nematic liquid crystals are used, the phase of a light beam can be changed without affecting the polarization of the light. Here as well, however, the light must be linearly polarized in parallel to the director of the oriented liquid crystal molecules. In addition, the reaction rate of such cells is too slow for applications in image-processing devices.

Ferroelectric liquid crystals (FLC) can be driven in a sufficiently short operation time. However, potential applications for ordinary ferroelectric liquid crystals are very limited due to the small phase changes that are attainable with. At cell thicknesses of  $10\mu\text{m}$ , phase shifts of merely about  $1/10$  of the wavelength of visible light are attained. However, one should aspire to phase shifts of one complete wavelength or more in order to perform all necessary phase corrections.

European Patent Application No. 0 309 774 discusses a liquid crystal cell which employs the DHF effect (deformation of the helix structure in the electric field) that occurs in FLCs, for continuous phase control and for gray scale representation. The optical phase control is based on a pronounced change in the average

refractive index of the liquid crystal resulting from an applied electric field. The change in the birefringence of the deformed helix structure can reach  $d(n) = 5\%$ ; the average refractive anisotropy  $\langle dn \rangle = 15\%$ . Due to the optical properties of the helical structure of thereby employed chiral smectic liquid crystal in the electric field, the change in the birefringence is associated with marked changes in the orientation of the average optical indicatrix. This means that, after propagating through the liquid crystal, the light is in a polarization state which is heavily dependent upon the polarization state upon entry. This dependence precludes the use of the described cell for the required purposes.

The reference of Love, Restaino, Carreras, Loos, Morrison, Baur and Kopp: "Polarization Insensitive 127-Segment Liquid Crystal Wavefront Corrector", Adaptive Optics, vol. 13, pp. 228-290, Optical Society of America, Washington D.C., 1996, discusses an electro-optically functioning modulator for controlling the phase of unpolarized light is introduced that contains two liquid crystal layers of the nematic type, which are disposed one behind the other. As apparently discussed in the reference, the two nematic layers are situated such that the directors of the liquid crystals are disposed orthogonally to one another in the field-free state. However, as already mentioned above, the cell may be much too slow for the purpose aspired to.

#### SUMMARY OF THE INVENTION

The exemplary embodiment of the present invention is directed to providing an electrically drivable light modulator, whose switching time is on the order of 1060-460 seconds or less, given a maximum phase shift of over  $20^\circ$ , and which can steplessly vary the phase of an arbitrarily polarized light beam, without altering its



polarization state, and which is suited for fabricating highly resolving, adaptive optical devices, i.e., that is small, light, and low-loss.

5 An exemplary embodiment of the present invention provides that at least two layers of helical, smectic, ferroelectric liquid crystals, whose fast and slow optical axes, respectively, are disposed in parallel with the layer in question, and whose average optical  
10 anisotropy can be influenced by the action of the electric field, are situated one behind the other in the path of rays of a light beam to be modulated, and in that the directions of the fast and slow axes, respectively, of the individual layers are rotated relatively to each other in such a way that the polarization of the light  
15 beam is the same upstream and downstream from the modulator.

In this context, the "slow" axis corresponds to that  
20 direction in which the refractive index is the greatest. The "fast" axis is that direction in which the refractive index is the smallest. Thus, the phase of a light beam that is polarized in the slow direction is delayed substantially, and the phase of a light beam that is  
25 polarized in the fast direction is delayed to a lesser extent. Thus, in the case of arbitrarily polarized light, the anisotropy of the refractive indices alters its polarization state as it passes through the liquid crystal layers. The rotation of the individual layers  
30 relatively to one another is exactly calculated to again effect a reversal of the mentioned change in the polarization state of the subsequent layers.

35 In a simple case, the light modulator is so conceived that two liquid crystal layers are situated one behind the other such that the slow optical axis of the first

layer is normal to the slow optical axis of the second layer, the fast optical axis of the first layer is normal to fast optical axis of the second layer, and the orientation of the slow and fast optical axes of the two layers in relation to one another is retained at all times during application and variation of the control voltage.

The fast and slow axes of the two layers intersecting at right angles only just compensates for the variations in the birefringence and in the orientation of the indicatrix ellipsoids of the refractive indices.

To reduce the unit volume, provision can be made for the liquid crystal layers to be enclosed between two transparent plates, on whose electrodes a control voltage can be applied to generate an electric field.

To reduce the outlay for assembling the light modulator and to facilitate mass production, provision can alternatively be made for each of the liquid crystal layers to be enclosed between two transparent plates, on whose electrodes a control voltage can be applied in each case to generate an electric field.

To manufacture the light modulator in accordance with the present invention, the required number of individual cells, fabricated in this manner, is arranged one behind the other.

When using comparable layer thicknesses and materials for the layers, it is provided that the liquid crystal layers exhibit the same average refractive indices, have the same thickness, and be able to synchronously receive the same control voltages.

When using different layer thicknesses or different materials for the individual layers, it is provided that the ratio of the control voltages to one another be adjustable to compensate for the changes in the polarization of a light beam passing through. In this manner, a crossing over of the main refractive directions can also be achieved in the case of asymmetrically constructed cells.

Considerable outlay is required to manufacture the liquid crystal cells; large quantities do not meet the requirements for accuracy and must, therefore, be sorted out and reintroduced to the production process. To simplify production and reduce associated costs, it is provided that the control voltages be adjustable for the individual liquid crystal layers to compensate for manufacturing tolerances.

The light modulator in accordance with the exemplary embodiment of the present invention is believed to work particularly well in the range of visible light with a smectic liquid crystal mixture FLC-472/FLC-247 of 60 % by weight of phenyl pyrimidine and 40 % by weight of an achiral, smectic A or C matrix having a chiral doping on the basis of disubstituted ether of bis-terphenyl dicarboxylic acid. This doping induces a spontaneous polarization of about 160 nC/cm<sup>2</sup> in the matrix having a helical structure of the winding period of about 0.3  $\mu$ m in the chiral smectic phase. An operating voltage of 0V to 4V already produces a smectic deflection angle of 0° to  $\pm 22.5^\circ$  at a response time 122 of 150  $\mu$ s. Thus, the modulation depth between two crossed layers amounts up to 100%. In response to the operating voltage mentioned above, the average refractive index already changes by amounts of up to 5%. To obtain a phase difference on the order of the wavelength of the light to be controlled, a

summed layer thickness of 10  $\mu\text{m}$  suffices. This layer thickness is the sum of the thicknesses of the individual layers.

5 When cameras or telescopes are used to observe objects within or right through the earth's atmosphere, local unsharpness occurs in the object image which is attributable to atmospheric disturbances. To correct this local unsharpness, an adaptive optical device is proposed  
10 which contains a field of light modulators, in a raster-type array, of the type described by the present invention. The field is situated in the path of rays of the device, each individual light modulator being able to be driven to compensate for unsharpness occurring on a  
15 point-by-point basis, of an image to be processed.

In this context, to reduce the outlay for assembly, the light modulators can be mounted on a common substrate.

20 The device is positioned in the ray path of the observational equipment in question, such as a camera or telescope. The object image picked up by the observational equipment is fed to an image-analysis device, which determines the unsharpness in the image  
25 and, to compensate for the same, drives the modulator field accordingly.

#### BRIEF DESCRIPTION OF THE DRAWINGS

30 Figure 1 shows the configuration of the liquid crystal cells for the modulator.

Figure 2a shows a schematic diagram of the refractive index indicatrices for an operating state where no voltage is applied.

35 Figure 2b shows a schematic diagram of the refractive

index indicatrices for an operating state where a small voltage is applied.

Figure 2c shows a schematic diagram of the refractive index indicatrices for an operating state where a voltage that is just below that voltage at which the helical structure of the liquid crystal disappears is applied.

#### DETAILED DESCRIPTION

Figure 1 shows an exemplary embodiment of the present invention having two liquid crystal layers 6 and 9 disposed one behind the other in the ray trajectory of a light beam 10 to be modulated. The polarization direction of incident light beam 10 and of emergent light beam 11 is marked in each case by a double arrow. In the example, the polarization direction of incident light beam 10 is tilted by angle  $\theta$  from the perpendicular.

First liquid crystal layer 6 is situated between two transparent electrodes 1 and 2, which are mounted on two transparent plates 1' and 2'. Smectic layers 12 form displacement domains, along which the molecules of the liquid crystal arrange themselves. The molecules of the liquid crystal are twisted by an angle from layer to layer, so that the result is a helical structure whose axis 7 runs in the direction of normals  $z'$  to smectic layers 12. Second liquid crystal layer 8 is disposed between transparent electrodes 3 and 4, which are mounted, in turn, on transparent plates 3' and 4'. The direction of normal  $z''$  of smectic layers 13 of 122 second liquid crystal layer 8 and the axis of helix 9 are twisted by 90° from direction of normal  $z'$  and helical axis 7 of first layer 6.

Two liquid crystal layers 6 and 8, crossed in this manner, change the polarization state of a transmitted

light beam 10. The pure phase modulation of the two liquid crystal layers is induced by the field-dependent, average refractive index. The birefringence and orientation effects of the indicatrix in the electric fields produced by the application of a voltage to connection terminals 5 are compensated in all field strengths.

Figure 2 shows effects of an electric field  $E$  of variable strength  $0, E', E''$  on refractive indices  $n_{20s20}$  and  $n_{20p20}$  of liquid crystal layers 6 and 8. The  $x$ - and  $z$ -axis of the illustrated coordinate system are disposed in parallel to the plane of the liquid crystal layers. In addition, the  $z$ -axis is situated in parallel to the direction of normal  $z'$  of first liquid crystal 6. The  $y$ -axis points in the direction of propagation of incident light beam 10. In Figure 2a, no voltage is applied. The slow axis having refractive index  $n_{20p20}$  of the first liquid crystal layer points in the direction of the  $z$ -axis, while the slow axis having refractive index  $n_{20p20}$  of the second liquid crystal layer is oriented orthogonally to the  $z$ -axis. The polarization state of the incident light is retained upon passing through both layers 6 and 8.

In Figure 2b, a small voltage is applied which is less than that voltage at which the helical structure disappears. The slow optical axes having refractive indices  $n_{20p20}'$ , as well as the fast axes having refractive indices  $n_{20s20}'$  of both layers 6 and 8 reorient themselves and are rotated by angle  $\theta$ . The right angles between the axes are retained. The  $122$  refractive index  $n_{20p20}'$  increases in the slow axes with rising field strength  $E'$ , while refractive index  $n_{20s20}'$  decreases in the slow axes. The optical path of the transmitted light is changed by field strength  $E'$  and,

consequently, is shifted in phase. The greatest change in the optical path occurs at a voltage that is just below that voltage at which the helical structure of the liquid crystal disappears. This state is shown in Figure 2c. In the liquid crystals, which at this point are no longer wound, the index ellipsoid of the refractive indices is characterized by molecular refractive indices  $n_{20p20''}$  and  $n_{20s20''}$ . The slow axes having refractive indices  $n_{20p20''}$  are tilted in the two layers 6 and 8 by the molecular tilt angle  $T$ , which corresponds to the angle between smectic layers 12 and 13 and helical axes 7 and 9. In this case, as well, the axes remain crossed at a right angle. The phase displacement is, therefore, independent of the polarization of the light over the entire operating range. As a result, it is possible to control unpolarized light as well.

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**DECLARATION AND POWER OF ATTORNEY**

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am an original, first and joint inventor of the subject matter which is claimed and for which a patent is sought on the invention entitled **ELECTRO-OPTICAL LIGHT MODULATOR**, the specification of which was filed as International Application No. PCT/EP99/08206 on October 29, 1999 and filed as a U.S. application having Serial No. 09/856,108 on May 17, 2001, for the Letters Patent in the U.S.P.T.O.

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims.

I acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations, § 1.56(a).

I hereby claim foreign priority benefits under Title 35, United States Code, § 119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application(s) for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

**PRIOR FOREIGN APPLICATION(S)**

Number	Country Filed	Day/Month/Year	Priority Claimed Under 35 USC 119
198 52 890.6	Fed. Rep. of Germany	17 November 1998	Yes

EL 244507410 US



3' And I hereby appoint Richard L. Mayer (Reg. No. 22,490), Gerard A. Messina (Reg. No. 35,952) and Linda M. Shudy (Reg. No. 47,084) my attorneys with full power of substitution and revocation, to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith.

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful and false statements may jeopardize the validity of the application or any patent issued thereon.

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